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The Spatial Variability of Turbulence above a Forest

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With 5 Figures

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Summary

The spatial variability of turbulence above a forest has been examined. Two measurement towers were erected 800 m apart within a heterogeneous mixed forest located in the north east of the Netherlands. The measurements of u^*/u were analysed and subsequently used to test a surface layer model. The model simulated the magnitude of the measurements reasonably well, but measured trends were not always reproduced by the model. The variable $(du/dz)/u$ did not adapt as quickly to the new surface as u^*/u. This is in agreement with Schmid (1994), and can be explained by a local decrease in mixing length. It is recommended to adapt the mixing length near a surface transition to improve the accuracy of surface layer models of heterogeneous landscapes.

1. Introduction

During recent decades many meteorological measurement campaigns have been executed above and within different types of extensive areas of homogeneous vegetation. The land-atmosphere interaction over homogeneous vegetation is by now fairly well understood (Veen and Dolman, 1989). In cultivated landscapes, however, many small scale vegetation patches occur, with accompanying scientific complications. Advection is one of the phenomena which have to be taken into account. The air stream over heterogeneous landscapes never reaches equilibrium and is continuously influenced by the underlying patch dynamics. At each transition in surface characteristics, a new Internal Boundary Layer (IBL) will be formed, where the flow is influenced by the new underlying surface. Advection terms might be important on a landscape scale (Klaassen and Claussen, 1995) when averaging fluxes and roughness parameters.

A particular complication occurrs near a transition between low vegetation and forest. In addition to a change in roughness, a change in porosity and effective height of the surface (zero-plane displacement) has to be taken into account. This complicates the transition process (Gardiner et al., 1995; Irvine et al., 1997). Forest edges cause strong local perturbation of the flow (Veen et al., 1996). Decreases of diffusivity down to 60% can occur after a grass-forest transition, which slowly recover to normal values at more than ten times the canopy height (Kruijt, 1994). This diffusivity influences the atmospheric exchange. Kruijt, however, had only one measurement tower at his disposal. In this current study two measurement towers were erected within a heterogeneous forest. This leads to opportunities to study the spatial variability of turbulence within a heterogeneous forest in a more in depth manner. Our objective is to study the surface-atmosphere exchange over a heterogeneous landscape. Measurements from both towers will be used to test a surface layer model (Klaassen, 1992).

2. Site Description

The measurement site is situated in the north east of the Netherlands (53° 01′ N, 6° 25′ W), near Veenhuizen. The "Bankenbosch" forest area is a small scale patchy mixed forest, situated next to the Fochteloërveen Bog area. The forest covers a total area of about 1.2 km^2 and contains several small tree patches varying in area from 3500 to 71000 m^2. The patches vary considerably in age, height and Leaf Area Index (LAI). The most common species found are Beech (*Fagus Sylcatica*), Douglas Fir (*Pseudotsuga menziesii*), Summer oak (*Quercus robur*), Scotch Pine (*Pinus Sylvestris*) and Japanese Larch (*Larix Kaempferi*). The height of the stands varies between 4.2 and 28 m, with maximum LAI's varying from 1.3 to 6.1 (m^2/m^2). The stand around the tower (erected for the Surface Layer Integration, Measuring and Modelling-Project at the Groningen University, here after called as the SLIMM tower), consists of Summer oak (*Quercus robur*) with an average tree height of 20.5 m. The tree density is 178 trees/hectare. It can be characterised as an open patch, with a LAI of 2.5, measured in September with a LICOR LAI-2000. The under canopy of the patch consists mainly of several grass species, blackberry (*Robus fruticosus L.*) and common polypody (*Polypodiaceae Vulgare L.*). The soil of the area consists of humus with sand (with iron precipitation), and loam underneath (van der Meulen and Klaassen, 1996). Slope within the area is negligible.

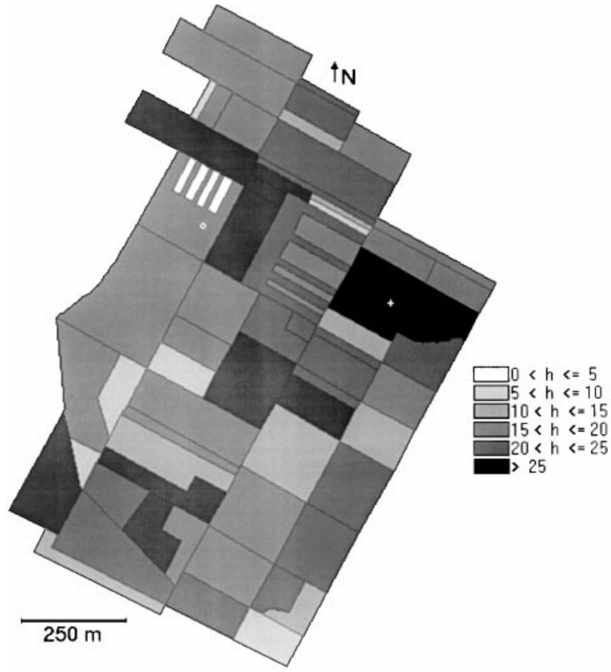

Fig. 1b. The average tree height (m) of the patches in the "Bankenbosch" wood. The SLIMM tower is marked with a +. The WSC tower with an ○. The north is indicated with an arrow

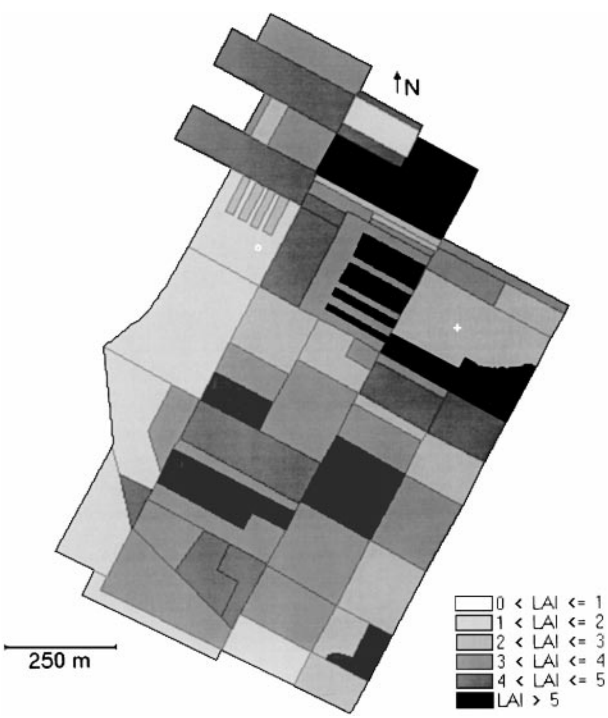

Fig. 1a. The Leaf area index (LAI) of the patches in the "Bankenbosch" wood. The SLIMM tower is marked with a +. The WSC tower with an 0. The north is indicated with an arrow

A measurement tower of the DLO-Winand Staring Centre (here after called the WSC tower) is also situated in the "Bankenbosch" forest, 800 m west of the SLIMM measurement tower. It is situated 150 m from the west edge of the forest itself. The patch vegetation consists of Japanese Larch (*Larix Kaempferi*), with an average tree height of 19.7 m, and in September a measured LAI of 1.3. Figure 1a and 1b show the average LAI and tree height for the patches within the forest. The measurement towers are also marked on the figures.

3. Material and Methods at the WSC- and SLIMM-tower

The SLIMM tower is 60 m high, which is three times the tree height. The tower consists of a thin tripod frame with a diameter of 1.5 m, and ten long booms, 4 cm in diameter, oriented at 190° at a height of 6, 12, 18, 21, 23, 26, 30, 36, 46, & 60 m. On these booms'fast-response' cup anemometers (design by Dept. of Meteorology, Agricultural University of Wageningen) were mounted, extending 2.5 m from the tower. Wind direction was measured with vanes (Vector) at 25 and 60 m. The incoming- and outgoing-, long- and short-wave radiation were measured with Kipp pyrano- and pyrgeometers (two ventilated CM11 and two ventilated CG1, all with CV1). The leaf wetness index (Campbell, model 237), and the infrared radiation temperature (Heimann, KT15) of the canopy were also stored. The half hourly averaged data, and their standard deviations, were stored with six Campbell CR10 data loggers. These data loggers were connected through a glass fibre system to a personal computer in a nearby container. Digital data transmission was chosen to minimise quality loss of the data during down loading. The cup anemometers were calibrated annually in a wind tunnel. Their accuracy was 0.1 ms^{-1}. For more detailed information about the site and the respective measurement towers we refer to van Breugel (1997) and Elbers et al. (1996).

Turbulence is measured directly with an eddy correlation set, consisting of a Gill 3d sonic anemometer (Solent 1012R2) and a Krypton hygrometer (KH20) at the WSC tower. This set is placed on a moveable vertical boom, with an operational height of 27 m. The eddy correlation data are processed with rotation corrections (McMillen, 1988), frequency-response corrections (Moore, 1986) and density fluctuation corrections (Webb et al., 1980). Other measurements used as model input for this analysis, are a cup anemometer (Vector), wind vane (Vector), air thermometer (Vaisala), slow hygrometer (Vaisala), an upwards mounted pyranometer (Kipp & Zonen CM21) and a pyrgeometer (Kipp & Zonen CG1). The data were processed and collected with a HP100 palmtop and a Campbell CR10 data logger.

At the SLIMM tower, the cup anemometers were used to calculate the variable $(du/dz)/u$ as a measure of turbulence. The gradient du/dz is taken as the finite difference of measurements between levels at 21.4 and 25.8 m; the vector u as the average at these two heights. The relation between $(du/dz)/u$ and u_*/u is described as:

$$\frac{\left(\frac{d\bar{u}}{dz}\right)}{\bar{u}} = \frac{u_*}{\bar{u}} \cdot \frac{\Phi_m}{l_m} \tag{1}$$

where Φ_m is a stability parameter and l_m is the mixing length (m), a measure of the ability of turbulence to cause mixing (Stull, 1988).

4. Model Description

The data are used to validate the two dimensional model of Klaassen (1992). This is a surface layer model with a first order mixing length closure. In order to satisfy two-dimensionality, the vegetation is assumed to be homogeneous in the horizontal plane.

Model input consists of vegetation characteristics, incoming shortwave and longwave radiation, temperature, humidity and wind speed at boundary layer height. The simulation starts with a single layer of vegetation, with a roughness length of 0.05 m and albedo of 0.10. Here, the momentum stress τ is calculated by the friction velocity u^*, which in its turn is calculated by wind speed at z_i and the roughness length and stability correction. Fluxes of sensible and latent heat are calculated with the simulated surface and air temperature and (saturated) vapour pressure, in combination with stomatal and atmospheric resistances. Downwind, the forest itself is modelled with a multi-layer approach with nine horizontal layers, each with a specific height interval and LAI distribution. Within the canopy, drag forces, available energy, wind speed, stomatal and atmospheric resistances and fluxes are calculated for each layer. An extension for counter-gradient transport within the vegetation is implemented within the forest to simulate higher and more realistic wind velocities. The calculated mixing length l_m, corrected for the conversion of turbulence to smaller eddies within the vegetation, is used to find a realistic roughness length and displacement height. Above the canopy height, atmospheric fluxes are related to the mixing length.

The mixing length is allowed to advect at the step-change of vegetation and Leaf Area Index; furthermore it is corrected with a constant 'rate of adjustment' to obtain a correct logarithmic wind profile after a long fetch. Pressure effects at the forest edge and Coriolis force are not included. The model was originally designed to predict average regional fluxes in heterogeneous landscapes with a large number of step-changes in vegetation between forest and grass. The model is slightly modified to simulate the heterogeneous forest more accurately and to calculate a flux at a specific height above a forest, after having passed a single grass-forest transition. The measurements at the tower are simulated using the measured wind direction to derive the appropriate fetch within the forest. The suitable fetches, LAI distributions and the different heights of the consecutive forest patches, are estimated from "Bankenbosch" patches near the measurement sites, and implemented in the model.

For the WSC measurement tower, five wind directions (95°, 180°, 225°, 270° and 315°) with specific upwind vegetation characteristics have been selected, with respectively a distance of 1400, 1125, 600, 150, 750 m towards the upwind forest edge. The model's meteorological input variables were evaluated from the data. The atmospheric stability (z/L) of these measurements varied between -1.29 and 1.55, and has been divided between stable (>0.03) and unstable (<-0.03) atmospheric conditions. At each selected wind direction and measurement site, three to four measurements were sampled for simulation by the model.

5. Results and Analysis

Results are presented from observations made during August 1996 from the both towers, and during September 1996 from only the SLIMM tower.

The windspeeds for both towers are compared in Fig. 2. Wind speeds below 0.5 m s^{-1} have been left out due to stalling errors. The data fit the 1:1 line fairly well. Differences can be explained by

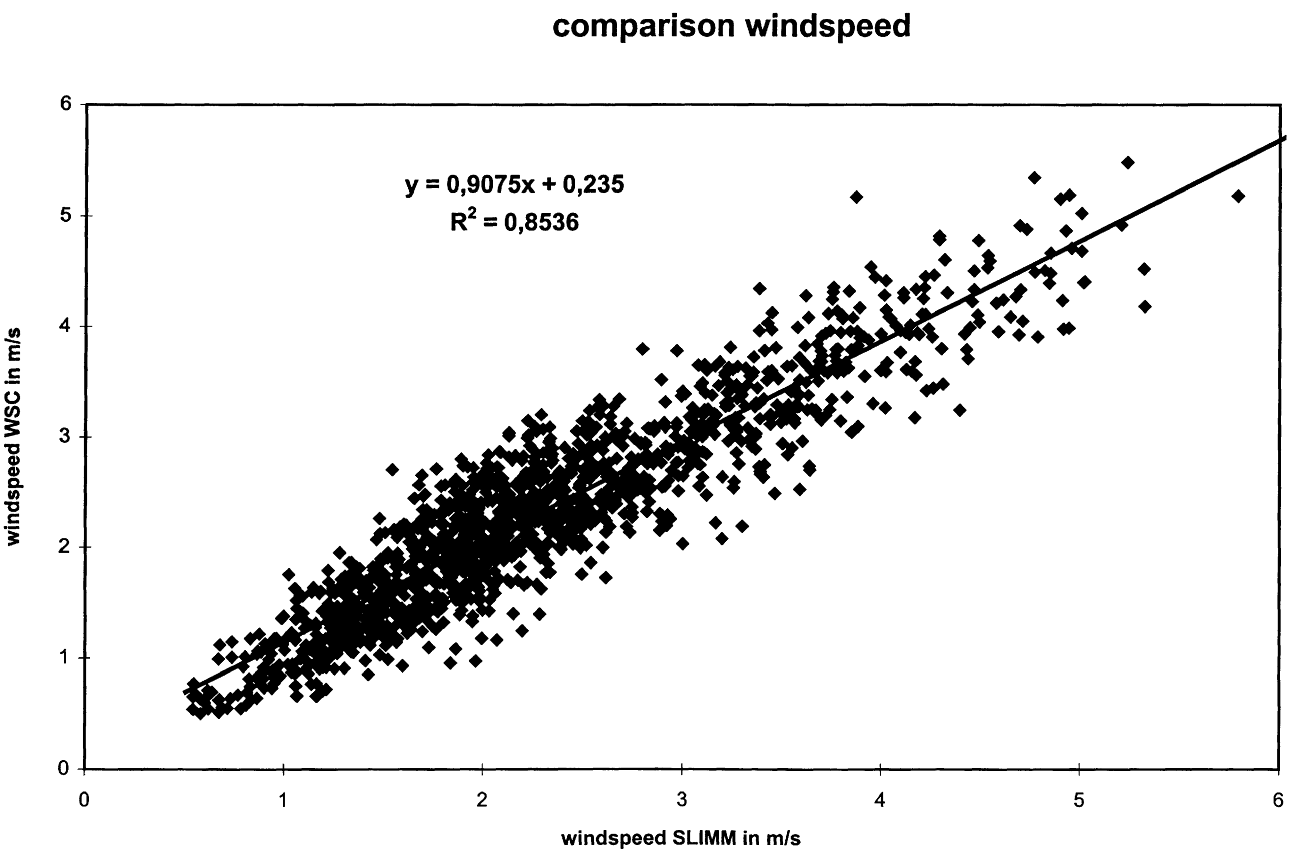

Fig. 2. Comparison of wind speeds (ms^{-1}) measured with cup anemometers at SLIMM and WSC site, averaged over half an hour

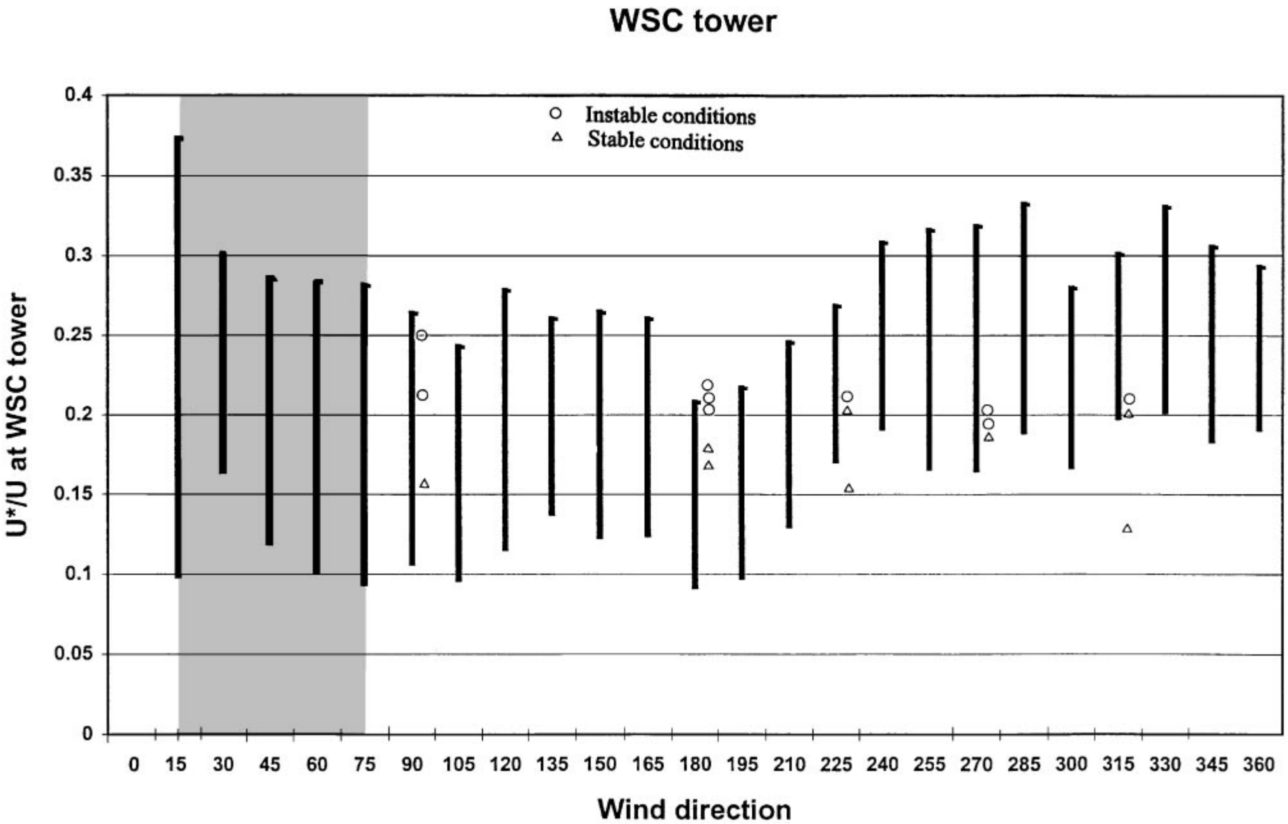

Fig. 3. u_*/u against the wind direction at the WSC site. Also the model output is shown. The shaded area of wind direction is showing measurements possibly disturbed by the tower

the varying fetch length over the forest and the different measurement heights. The measurement heights (z-d, with d being the displacement height) for the WSC and SLIMM sites are 13.1, and 12.1 m respectively.

Figure 3 shows the measured variable (u_*/u) at the WSC tower, plotted against wind direction. The vertical bars denote the 15° average plus/minus one standard deviation. In the shaded area of the figure the measurements may be disturbed by the tower. The model output for five specific wind directions has also been added. In the measured turbulence parameter u_*/u we can detect local minima for two wind directions. At 105° and 180° the adjacent upwind tree patches are considerably higher (25.4 and 25.2 m) than the measurement site (19.7 m), causing a local decrease in u_*/u. At 270° the distance towards the forest edge is minimal, being 150 m or roughly seven times the tree height. u^*/u appears to be up be up to 20% higher in this region. This is in agreement with Gash (1986) who states that u_*/u adapts quickly to the new surface.

The model seems to simulate the magnitude of the variable u_*/u reasonably well, although the observed trend between 95 and 315° is not clearly followed by the model. The poor simulation of the trend is attributed to the slow adjustment of the mixing length in the model.

Figure 4 shows the normalised shear $(du/dz)/u$ against wind direction between levels at 21.4 and 25.8 m measured at the SLIMM tower. The sectors where the measurements might be disturbed by the tower are shaded. The variable $(du/dz)/u$ is not corrected for stability and is related to local turbulence (see Eq. 1). Peaks occur between 30 and 60°, between 165 and 210° and between 315 and 345°. The peaks may have several causes. A possible explanation could be a strong dependence of atmospheric stability on wind direction, as different weather regimes are correlated with wind direction. However, the

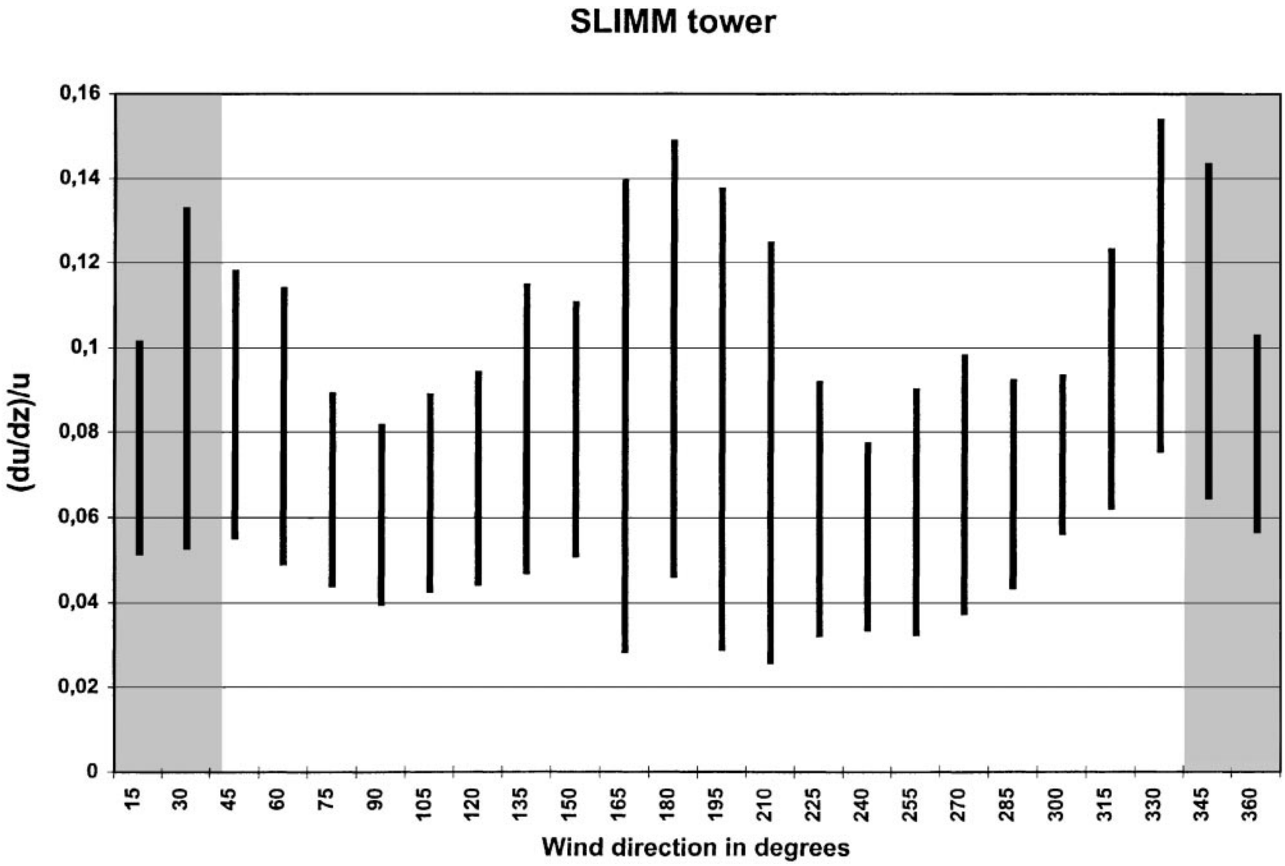

Fig. 4. The variable $(du/dz)/u$ against the wind direction at the SLIMM site. The shaded area of wind direction is showing measurements possibly disturbed by the tower

measurements did not reveal any dependence of a stability parameter on wind direction. The results might also be caused by the limited measurement heights, which are well within the roughness layer. This explanation is unlikely as the patch itself is rather homogeneous. Rather, it is expected that the peak is caused by a difference in patch characteristics along the air flow path, like a difference in vegetation height. The peak between 165 and 210° can be explained by the upwind patch being on average 3.4 m lower. The nearest forest edge lies between 330 and 60°. This edge is the most probable cause for both the peaks between 315 and 345° and between 30 and 60°. The smaller dip in the variable between these peaks seems to be a natural variation in the signal.

Between 315 and 345° the peak in $(du/dz)/u$ has a value of about 160% of the average value. As u^*/u adapts quickly, and a dependence of stability on wind direction does not occur, the mixing length has to decrease locally (see Eq. 1). This is in agreement with Kruijt (1994). According to Kruijt, the diffusivity, and therefore the mixing length, can decrease down to 60% of its equilibrium value after a grass-forest transition. This slowly recovers to normal values after more than ten times canopy height. In this situation, here the fetch in the region of the peak varies between 125 and 250 m, being roughly 6 to 12.5 times canopy height.

The variable $(du/dz)/u$ is plotted versus wind direction at several vertical levels in Fig. 5. The measurements averaged over 15° are shown and this variable decreases with height as expected. The percentage change in the mean with wind direction tends to decrease above levels of 25.8 m. Even between 30.5 and 36.3 m the increase or decrease in the signal can become as large as 60%. The variation in the signal between 30.5 and 36.3 m can not be explained by the higher noise/signal ratio alone, for the

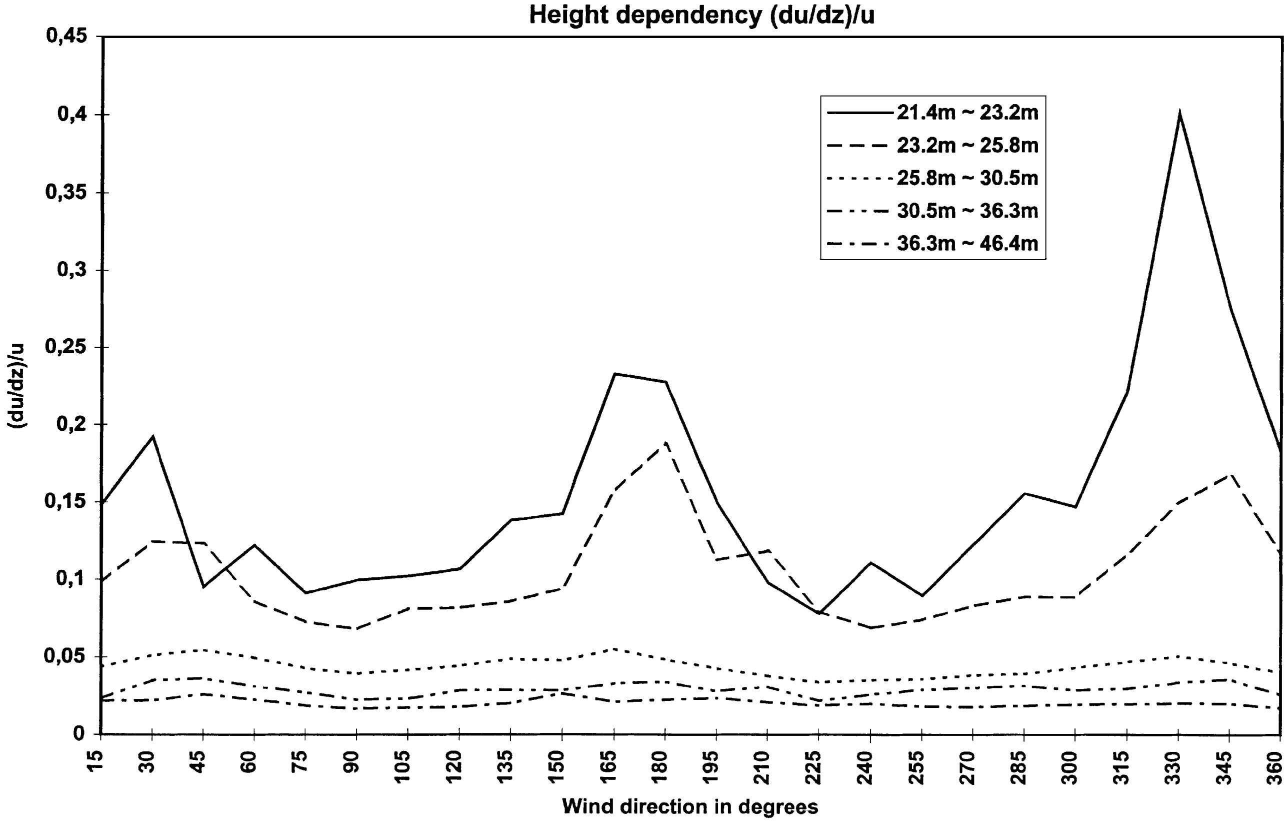

Fig. 5. The averaged variable $(du/dz)/u$ at the SLIMM site against the wind direction and height

standard deviation (not shown here) decreases strongly from $0.15\,\mathrm{m}^{-1}$ between 21.4 and 23.2 m to values of $0.02\,\mathrm{m}^{-1}$ between 30.5 and 36.3 m. The variation in the signal can be explained by the influence of larger scale variations.

Below 25.8 m fluxes the strong variation in the trend of $(du/dz)/u$ with wind direction suggests that at fetches of 125 to 250 m, in the region of the peak, the diffusivities and windspeed gradients are not yet in equilibrium with the surface. Gash (1986) found a fetch over height ratio for the so-called Equilibrium Layer (EL) for fluxes of between 16 and 27 after a heath-forest transition. Schmid (1994) stated that the source area for scalars tends to be larger than the source area for fluxes by approximately an order of magnitude. This is in agreement with our findings.

6. Conclusion

In this article we have analysed the influence of forest heterogeneities on atmospheric flow measurements. The dependence of u^*/u on wind direction at the WSC site can be explained by the variation in fetch. The data were used to validate a surface-layer model, which simulated the magnitude of u_*/u reasonably well. The variable $(du/dz)/u$ adapted more slowly to the new surface as u_*/u. This can be explained by a local decrease in mixing length and by the footprint for scalars, which is larger than for fluxes. The temporary decrease in diffusivity downwind of a transition in vegetation height (within ten times canopy height) influences the atmospheric exchange over heterogeneous forest on a landscape scale. The mixing length in simulation models should therefore be adapted to improve model accuracy.

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